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Precipitation Thresholds for Triggering Floods in the Corgo Basin, Portugal

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Abstract: Thresholds based on critical combinations of amount/duration of precipitation and flood events were estimated for the Corgo hydrographic basin, in northern Portugal. Thirty-one flood events in the Corgo basin were identified between 1865 and 2011 from a database of hydrometeorological disasters in Portugal. The minimum, maximum, and pre-warning thresholds that define the boundaries for flood occurrence were determined. The results show that the ratio between the total number of floods and precipitation events exceeding the minimum threshold denotes a relatively low probability of successful forecasting. This result may be due to the reduced number of flooding events in the floods database, which only include floods that caused damage as reported by the media. The estimated maximum threshold is not adequate for use in floods, since the majority of true positives are below this limit. However, and more interestingly, the retrospective verification of the estimated thresholds suggests that the minimum and pre-warning thresholds are well adjusted. Therefore, the application of these precipitation thresholds may contribute to minimize possible situations of pre-crisis or immediate crisis by reducing the flood consequences and the resources involved in emergency response to flood events.

Keywords: precipitation; thresholds; floods; database

1. Introduction

Precipitation is a major cause of natural hazards and is related to flooding [1–3]. The severity of a precipitation event and its potential damage is dependent on the total amount of rain and also on its intensity and duration [1]. Therefore, it is of utmost interest to estimate the precipitation thresholds and test their usefulness for the prediction of floods. "A threshold is the minimum or maximum level of some quantity needed for a process to take place or a state to change" [4]. Precipitation threshold is defined as the cumulative precipitation amount, for a given time period and a soil condition, that generates critical runoffs high enough to provoke damage [5] and can be used as a first step to initiate flood warnings before performing hydrological simulations [5–7].

Several works have focused on the estimation of precipitation thresholds and their use in the prediction of landslides triggered by precipitation [4,8–23]. In spite of being considered one of the emerging approaches in flood forecasting [6], applied research to flood-related precipitation thresholds have been more limited than the applied research to landslides [24].

Hapuarachchi, et al. [25] classifies the different approaches in flood forecasting as follows: (1) flood susceptibility assessment procedures; (2) precipitation comparison methods; and (3) flow comparison methods. A typical flood forecasting system based on a hydrological model generally requires the availability of real-time data of flow and precipitation. Bracken, et al. [26] or Kourgialas, et al. [27] defined precipitation thresholds for a given soil moisture condition. Most flood operating alert systems are based on precipitation and flow measurements. Alfieri and Thielen [28] developed an early warning system based on forecasts of accumulation of heavy precipitation in Europe. Between December 2009 and September 2011, they detected up to 90% of the events in Europe. Ávila, et al. [29] studied 27 floods that occurred between 1980 and 2012 in the hydrographic basin of the Cali River, Colombia. The analysis showed that the greatest determinant for the occurrence of floods is accumulated antecedent rainfall, with thresholds greater than 73, 95, 124, 170, 218, and 273 mm, for 5, 7, 10, 15, 20, and 25 days, respectively. Jang [5] developed an advanced methodology to improve the effectiveness of the warning precipitation threshold method for urban areas through deterministic-stochastic modeling. However, this work used short periods of precipitation values (<72 h). Papagiannaki, et al. [30] studied the flash flood events that occurred in the Attica prefecture, the most urbanized region of Greece and concluded that most of the events are associated with maximum accumulated rainfall of more than 20 mm in 24 h and 3 mm in 10 min.

The availability of data (precipitation and flow) with a sufficiently long period of records is one of the main constraints to develop a flood system. In this work, we can only use daily precipitation data to attempt an estimation of critical thresholds for flood occurrences as flow data in the Corgo basin are too scarce for a significant statistical analysis. Thus, to overcome this limitation, we will apply and test the methodology used in other studies on precipitation-triggered landslides in Portugal [8,12,16–18,22,23]. In order to determine the precipitation thresholds, we start with the assumption that critical combinations amount/duration of cumulative precipitation with a higher return period will be the most significant, from a statistical point of view, to trigger the occurrence of extreme events [8,12,16,18].

Thus, the main objective of this study is to determine critical precipitation thresholds of amount/duration, based on past flood events in the Corgo hydrographic basin in northern Portugal.

2. Materials and Methods

2.1. Study Area

The administrative region of Northern Portugal covers an area of ca. 21,278 km^2 that has a marked spatial heterogeneity of the mean annual precipitation totals, ranging from 600 mm in the upper Portuguese Douro Valley to 2700 mm in the Peneda–Gerês mountain range (Figure 1). The climate in the northwestern area is largely influenced by the proximity to the Atlantic Ocean. This west–east contrast is due to the mountain relief effect since the geographic orientation of the main mountain ranges is predominantly parallel to the coastline, thus blocking the moist westerly winds blowing from the North Atlantic [31,32].

The Corgo basin is located in a region where the pluviometric contrasts are very sharp between the wettest areas of the Alvão and Marão mountains and the drier sectors situated on the lee side (Figure 1). The Corgo basin covers an area of 469 km^2 with a drainage density of 3.8 km/km^2.

The highest altitude in the Corgo basin is located in the Serra do Alvão (1416 m) and the average slope is 14°; the higher slopes are situated in the terminal sector of the basin and exceed 70°. There are two distinct areas with different geological characteristics: one is located in the northern part of the basin occupying 50% of the area and is composed of Hercynian granites, whereas the other area is located in the downstream sector of the basin, close to the Douro River valley. It is constituted by metasedimentary formations (41%). 55% of the basin area is taken up by forests and 41% by agricultural lands. It is important to highlight the relevance of the vineyards in the land use of the terminal area of the basin. The urban occupation reaches 3.7%, which corresponds roughly to the city of Vila Real (Figure 2). The available quantitative data to evaluate the possible influence of land use changes in the Corgo basin is quite limited (or even absent from the 1940s to 1980s), hence it was not possible take into account this factor on flood triggering conditions to adjust the estimated precipitation thresholds.

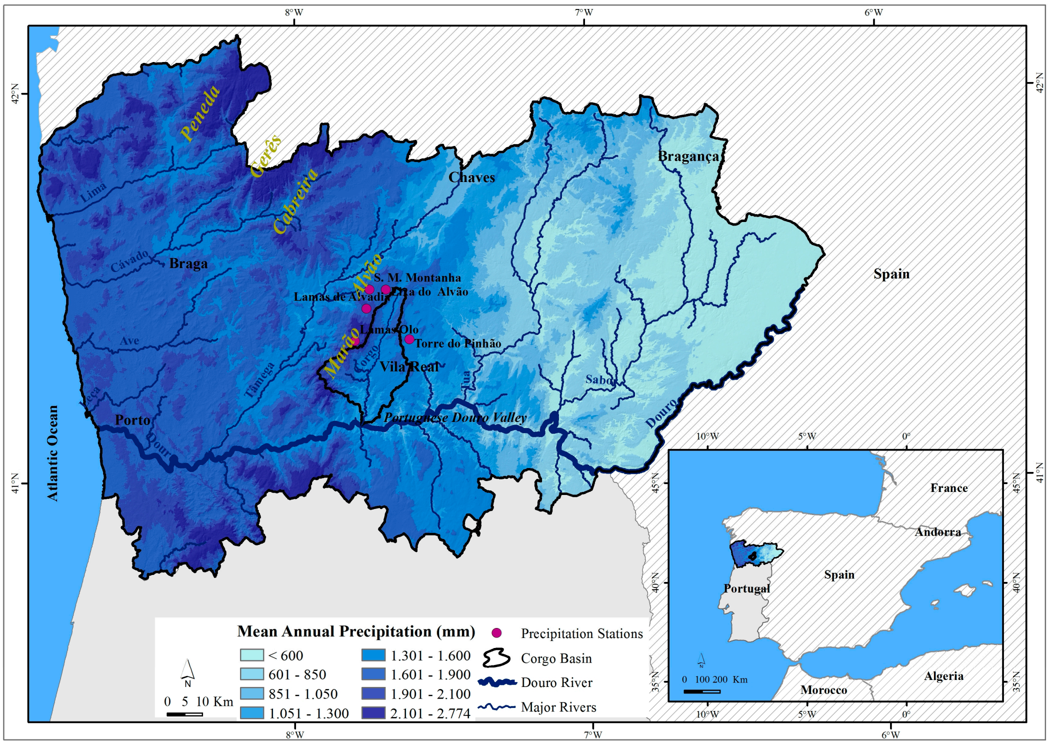

Figure 1. Location of Corgo basin in Northern Portugal and mean annual precipitation (1960–2000) in the study area.

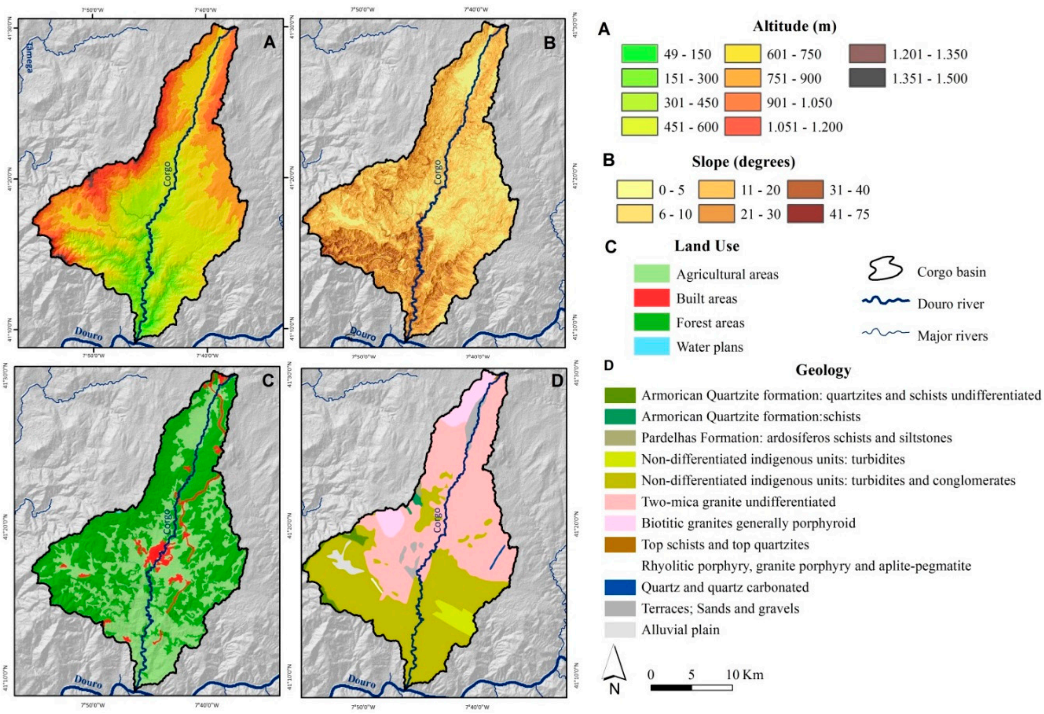

Figure 2. Geographical features of the Corgo basin. (**A**) Altitude; (**B**) Slope; (**C**) Land Use (Corine Land Cover, 2006); (**D**) Geology.

2.2. Flood Events and Definition of Critical Precipitation

In the present study, a flood event is defined as a flood that causes some kind of damage as reported by national and regional newspapers, regardless of the number of people affected or the economic value of the resulting damage [32]. The methodology used for the data flood collection and storage was described in detail in previous works [32–34] and the inventory of flood events in the Corgo basin was obtained from the DISASTER Database. A total of 145,709 newspapers, in a 147-year period (1865–2011), were analyzed for the construction of the database which is a unique historical data source for Portugal. It is assumed that damaging flood events are important enough to be reported by regional/local and national newspapers. For each flood event, the following information was collected: sub-type (i.e., river flood, flash flood, urban floods), date, location (municipality, parish and x/y-coordinates according to the PT-TM06/ETRS89 projected coordinate system), triggering factor, and information source (name, source type and reliability of the news, source, date of source, page number), number of deaths, injured, displaced, homeless or missing persons, the entities involved and material losses. As this dataset is developed in a GIS (Geographic Information System) environment, each occurrence is coded and georeferenced using a point shapefile.

Daily precipitation data of the five stations, from 1945/46 to 2000/01, were obtained from the National Information System for Water Resources (SNIRH) managed by the Portuguese Environmental Agency (APA). The next step in the data quality assessment was the verification and quantification of missing data. The Lamas do Olo series, has the highest number of missing data, although the gaps represent less than 3% of the total daily data. Given the low proportion of missing values in all daily precipitation series, it was decided that the missing data would not be filled in, a procedure that could itself introduce some inhomogeneity into the series. Potential inhomogeneities were identified using the number of wet days as the testing variable, as recommended by Aguilar, et al. [35]. We used the following homogeneity tests at 5% significance level: Pettit [36], SNHT—Standard Normal Homogeneity Test [37], Buishand [38] and Von Neumann [39]. All series were classified as homogeneous by all the tests.

The precipitation series (Figure 1 and Table 1) were organized in hydrological years (from October to September) and the maximum precipitation for different time intervals (1, 2, 3, 4, 5, 10, 15, 20, 30, 40, 50, 60, 75, 90 days), as well as the respective return periods were calculated. The calibration period is the 1945/46–2000/01 and de validation period is the hydrological year 2015/2016. Critical precipitation amount/duration was obtained for each flood event by objective method and include (i) the computation of cumulative absolute antecedent precipitation for 1, 2, 3, 4, 5, 10, 15, 30, 40, 60, 75, and 90 consecutive days; (ii) the calculation of the return period for the precipitation amount-duration combinations by applying the Gumbel distribution [40]; (iii) and the critical combination responsible for each flood event has been assumed as the precipitation pair (quantity-duration) with the highest return period [17,18].

Table 1. Mean, maximum, and minimum annual values of precipitation stations.

Precipitation Stations	Period Data	Mean Annual Precipitation (mm)	Maximum Annual Precipitation (mm)	Minimum Annual Precipitation (mm)
Lamas da Alvadia	1945/46–1997/98	1959.7	3680.9	871.0
Lamas de Olo	1945/46–1997/98	1621.8	3782.2	472.6
Lixa do Alvão	1945/46–1997/98	1386.1	2626.4	518.8
S. M. Montanha	1960/61–2000/01	1812.6	3675.5	980.6
Torre do Pinhão	1945/46–2000/01	1201.4	2156.8	740.8

Flood events with less than one-year return period were excluded from the study sample because there is a possibility of these events might be located in space (thus, not detected by rain gauges) or occurring at the beginning of the hydrological year and affecting stormwater drainage systems that respond to small quantities of precipitation. In this way, and as it was suggested by Ascenso [12], flood events with a return period of one year in all durations have not been considered in the preparation of the thresholds to prevent the increase in false positives.

The definition of the critical precipitation period associated to each flood event strongly influences the establishment of any empirical precipitation threshold for floods [16]. In this work, the critical precipitation is the combination of the higher rainfall quantity and rainfall duration for each flood event.

2.3. Precipitation Thresholds Normalized by the MAP

Next, and in order to validate the thresholds, the critical combinations of accumulated absolute precipitation, the duration of the events that triggered floods, as well as the records of maximum accumulated precipitation for different time intervals (1, 2, 3, 4, 5, 10, 15, 20, 30, 40, 50, 60, 75, 90 days) that occurred in years with no flood events were all considered for the precipitation station with the highest coefficient of determination (Lamas de Olo) between critical combination (quantity/duration). A normalization procedure was applied as recommended in previous studies (e.g., [8,12,41]) in order to reduce discrepancies in precipitation values due to the different elevations of the meteorological stations. Furthermore, this approach allows determination of the degree of demand required for a given threshold to be reached in each of the meteorological stations. The following equation was used for normalization:

$$\mathrm{Pn} = \mathrm{Cp}/\mathrm{MAP} \tag{1}$$

where: Pn is precipitation normalized by the mean annual precipitation (MAP) and Cp is the critical precipitation for different periods between 1 and 90 days.

2.4. Lower and Upper Limits of Precipitation Threshold and Validation

Finally, we will describe the procedure to determine the minimum and maximum thresholds (that define the lower and upper boundaries, respectively) of the probability of occurrence of a certain phenomenon. The method is based on the methodology applied to landslide forecasting by Oliveira [8] to the region north of Lisbon.

The lower limit threshold is determined, empirically, as the antecedent precipitation conditions below which no past flood event has been recorded, i.e., no false negative flood events are expected to occur below this limit. The upper limit threshold is determined, empirically, by the antecedent precipitation conditions above which flood events have been systematically recorded, i.e., no false positive flood events (dates where the precipitation values could trigger floods, but this is not verified). The probability space between both upper and lower boundaries defines the regional uncertainty [16] in the determination of the precipitation critical conditions for flood event initiation. The identification of these limits was made according to the following steps:

1. The minimum threshold was chosen as the linear regression of the critical combinations that triggered flood events. The minimum threshold is enclosed by two critical durations of different events and a new linear trend including all true positives.
2. The next step involves the determination of the maximum threshold. Thus, the linear regression line was set to the maximum combinations of quantity/duration associated with each of the years with no flood occurrences. Then, we designed the line to a greater magnitude, to select the two critical combinations that allow the absence of false positives and defined the potential regression line, in order to ensure a greater number of true positives above this limit.
3. This methodology also allows the definition of a pre-warning threshold, that is, when 90% of the daily precipitation required to overcome the minimum threshold for any duration is reached. The maximum values of precipitation for different periods (1, 2, 3, 4, 5 10, 15, 30, 40, 60, 75, and 90 days) of the years with no flood occurrences were used to validate the thresholds. In order avoid bias of the results, accumulated precipitation records that exceeded the minimum threshold for more than one critical duration, were considered only once, and in the case of separate independent events the precipitation values of different durations must be separated by one or more days. Thus, the validation is performed using the ratio between the total number of flood events and the total number of precipitation events which do not originate flood occurrences, although the amount of accumulated previous precipitation was above the threshold.

This calculation yields the probability of a precipitation event that exceeds the minimum threshold to trigger a flood event in the Corgo basin.

3. Results

The critical precipitation thresholds for flood triggering were estimated from an inventory of 16 flood occurrences in the Corgo basin, using the criteria explained in Section 2.2. Table 2 summarizes critical precipitation amount/duration, precipitation intensity/duration, and return period for each flood event. Critical combinations occur from 1 to 90 days and floods can ensue with different combinations of amount/duration of precipitation. The return period refers to the critical combination of the third column.

Table 2. Flood events triggered by precipitation in the Corgo basin from 1865 to 2011 (Meteorological station: Lamas do Olo).

Flood Event	Date (yyyy/mm/dd)	Critical Precipitation Amount/Duration (mm/dd)	Precipitation Intensity/Duration (mm·day^{-1}/dd)	Return Period (Years)
1	1947/02/05	1046.2/90	11.6/90	2.7
2	1947/02/22	1307.4/90	14.5/90	4.4
3	1948/01/28	705.4/30	23.5/30	4.2
4	1948/01/29	119.6/1	119.6/1	10.9
5	1948/12/12	176.4/4	44.1/4	2.0
6	1951/01/07	799.5/60	13.3/60	2.5
7	1951/01/28	1070.3/90	11.9/90	2.9
8	1951/02/05	1211.7/90	13.5/90	3.7
9	1951/02/21	397.6/5	79.5/5	15.8
10	1955/01/19	302.6/10	30.3/10	2.4
11	1956/03/29	179.4/10	17.9/10	1.4
12	1959/12/09	495/30	16.5/30	2.2
13	1963/02/16	290.8/2	145.4/2	104.5
14	1968/12/17	195.8/3	65.3/3	4.4
15	1979/02/13	986/75	13.2/75	2.9
16	1996/01/09	935.6/30	31.2/30	9.5

Most flood events occurred in years with heavy precipitation as shown in Figure 3. In the Corgo basin, the percentage of flood events that occurred in years with precipitation above the MAP reached 69%.

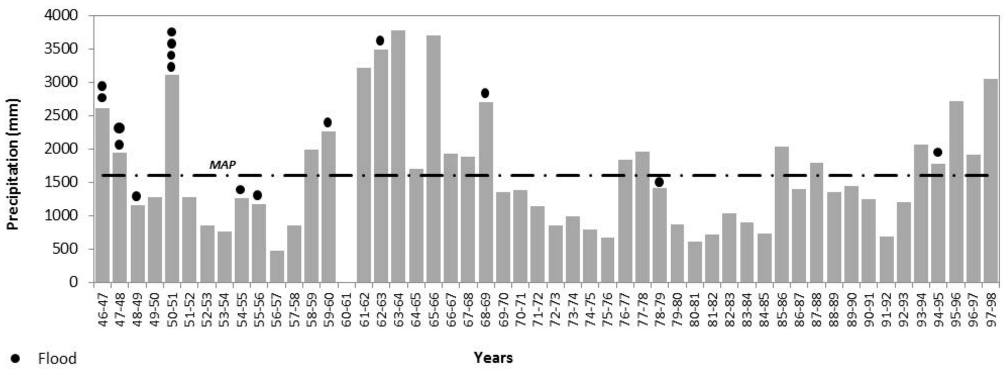

Figure 3. Annual precipitation (hydrological year) and flood events (Meteorological station: Lamas de Olo). Black line symbolizes mean annual precipitation (MAP) and dots indicate flood events.

However, the occurrence of flooding can be associated to intense precipitation periods concentrated in just a few days, independently of the previously accumulated precipitation. On 16 February 1963, 291 mm of precipitation were recorded in two days, with an estimated return period of 105 days.

Figure 4 shows the quantity–duration precipitation threshold in the Corgo basin, defined by linear regression of these variables over the 16 flood events. A strong correlation ($r^2 = 0.88$) was found between the absolute previous precipitation and the critical duration for each flood event (green triangles) for the Lamas do Olo station. The regression line is given by equation: $Cr = 10.51D + 231.49$ where Cr is the cumulative precipitation in mm, and D is the duration in days. For every year without flood events, the yearly maximum precipitation values for consecutive durations of 1, 5, 10, 15, 30, 40, 60, 75, and 90 days were selected and plotted in Figure 4.

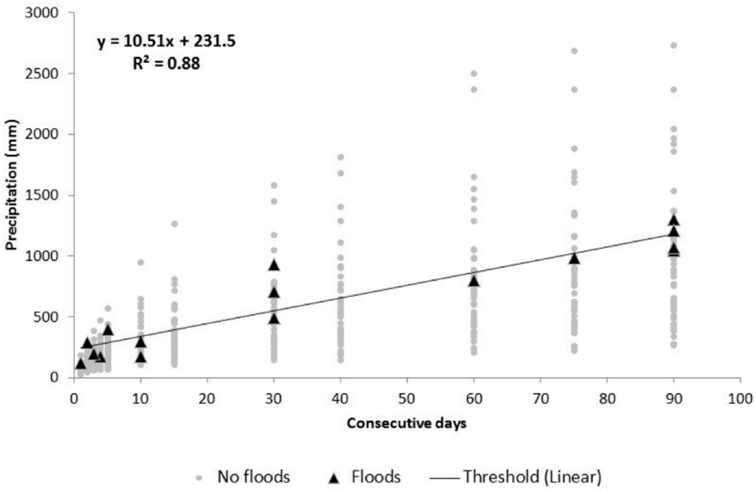

Figure 4. Precipitation quantity–duration threshold in the Corgo basin, defined by linear regression of flood events (Meteorological station:Lamas do Olo; Period 1946–1998).

Lower and upper limits of precipitation thresholds were defined for the Corgo basin taking into account the selected set of flood events triggered by precipitation from 1946 to 1998 (Figure 5). Figure 5 also includes, for validation, the potential regression line that best fits the distribution of flood events and the highest annual previous precipitation value for each combination of cumulative days (1, 2, 3, 4, 5, 10, 15, 20, 30, 40, 50, 60, 75, and 90) recorded in the years with no floods for the same period. The lower limit threshold is better fitted by a linear regression described by $y = 10.82x + 76.84$ which typifies the minimum precipitation conditions for flood triggering in the study area. The upper limit threshold is better estimated by the following potential law: $y = 183.48x^{0.65}$.

The comparison between flood events and events of precipitation above the threshold that did not trigger any floods shows that there is a probability of only 17.5% of a specified value of accumulated previous precipitation, exceeding the minimum threshold, to relate to a flood event.

In order to test the methodology of determination of critical precipitation thresholds, it was decided to choose two floods that occurred in the current hydrological year (2015/2016), more precisely on 10 January and 13 February 2016.

Thus, we can see that the pre-warning and minimum thresholds were reached in these recent events, while the threshold based on the events was only exceeded on 11 February. The maximum threshold was never exceeded (Figure 6). The threshold (black line), based on critical combinations of amount/duration of precipitation for past flood events, was exceeded in two events. Figure 7 confirms the durations for which the thresholds were exceeded. Thus, in the flood event of 10 January the pre-warming and minimum thresholds were reached for the previous accumulated precipitation of 2 to 40 days. In the flood event of 13 February the minimum threshold was exceeded for the duration of 2 to 90 days and 40 to 60 days and the pre-warning threshold was exceeded for durations of 2 to 75 days (Figure 7). In addition to the importance of the accumulated precipitation for longer durations, these floods were also controlled and triggered by the high amount of precipitation registered in the previous two days.

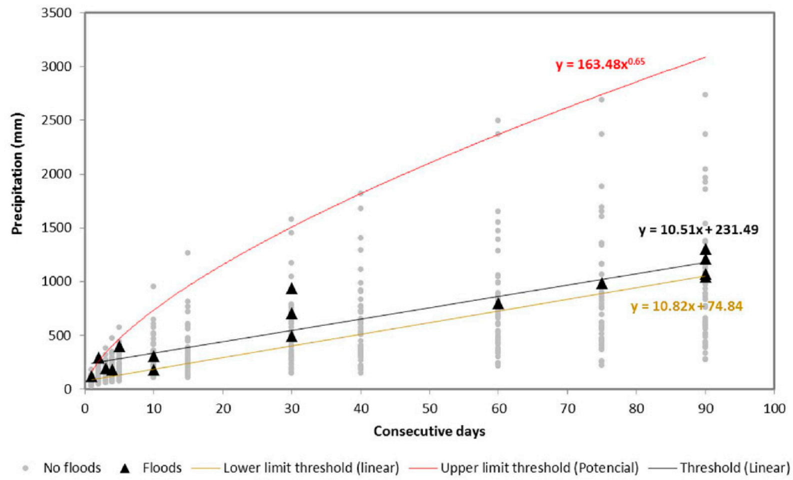

Figure 5. Lower limit and upper limit precipitation thresholds for the flood events in the Corgo basin.

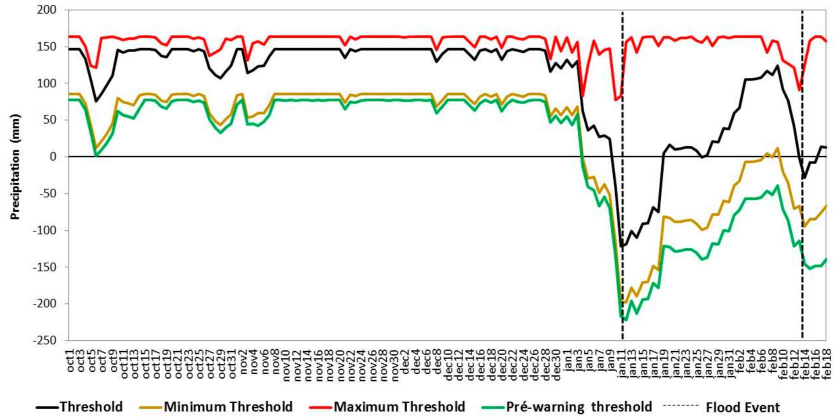

Figure 6. Thresholds of accumulated precipitation with different lengths and subsequent flood events: 10 January and 13 February 2016. Threshold of flood events (**black**); maximum threshold (**red**); minimum threshold (**yellow**); and pre-warning threshold (**green**). The broken lines indicate the flood events.

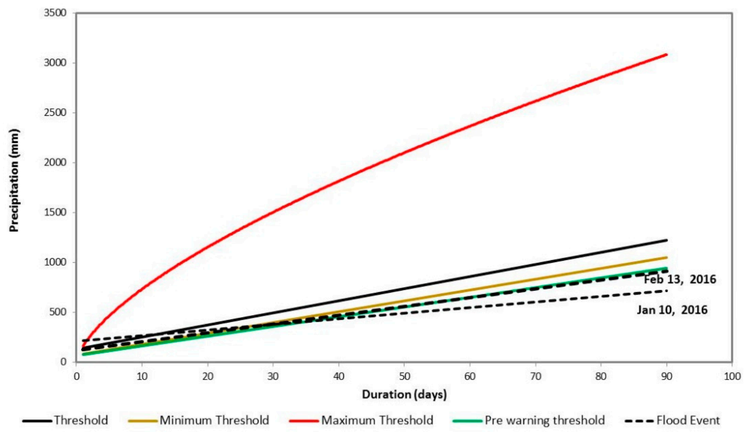

Figure 7. Minimum daily precipitation necessary to overcome the different thresholds of precipitation and flood events in 10 January and 13 February 2016. Thresholds based on flood events (**black**); maximum threshold (**red**); minimum threshold (**yellow**); and pre-warning threshold (**green**). The broken lines indicate the flood events.

4. Discussion

The present research focused on the determination of critical precipitation thresholds for flood triggering, assessed by an empirically based model supported by the historical record of floods in the study area taking into account the precipitation and conditions that preceded the event.

In the significant literature, two approaches have been proposed on precipitation thresholds for flood triggering: (i) empirical or statistical methods, for easier implementation; and (ii) physical, process-based models, which are more complex to define and apply [15,29,42]. A precipitation threshold (by statistical method) is generally obtained on a linear or logarithmic-scale graph by drawing the differentiation line between the precipitation features that cause floods and those that do not [42]. Some studies [4,43] that criticize these approaches, have introduced some statistical methods for the definition of more objective precipitation intensity-duration thresholds [42]. However, these methods involve hourly precipitation data (e.g., [5,14,20,30,42]) which in Portugal are too scarce or even absent in most drainage basins. Therefore, the empirical thresholds estimated in this study, are based on the identification of past flood events and include (i) the computation of antecedent precipitation threshold defined by linear regression; (ii) the normalization of precipitation by the mean annual precipitation; (iii) the definition of lower limit and upper limit precipitation thresholds; and (iv) the definition of combined precipitation thresholds, which integrates the precipitation event and the antecedent precipitation for different time periods.

The thresholds for the flood events in the Corgo basin were inferred from the available precipitation quantity and duration data. This is an innovative approach over the flood studies in Portugal. The benefit of this study is the creation of an easy to-use method that could be applied by the civil protection. The number of registered flood events in the study area is relatively low and this is a major limitation to establish reliable relationships between precipitation and floods. Overall, the estimated thresholds based on the critical combination amount/duration was satisfactorily adjusted in the study area. Another limitation is that the precipitation thresholds obtained are valid only for the Corgo basin. This constraint , as suggested by Huang, Ju, Liao and Liu [20], must be taken into account before applying the methodology to another area. The variability in precipitation thresholds can be due to several factors, such as: (i) lithological or morphological diversity, vegetation and soil conditions; (ii) different climatic regimes and weather circumstances; (iii) the heterogeneity and the incomplete precipitation data and floods used to determine thresholds.

The results suggest that the minimum and pre-warning thresholds were well adjusted and therefore represent a benefit in warning the authorities for the occurrence of flood events in the Corgo basin. We acknowledge that these findings need to be further confirmed in the near future, when further flood events will take place in the Corgo basin. As suggested by Bezak, Šraj, and Mikoš [14] a reasonable data length should contain at least approximately 10 flood events exceeding the flooding threshold. Furthermore, due to the complexity involving flood triggering, additional research is still needed, addressing other factors as land use changes. Nevertheless, after the validation exercise presented here, we are very confident that the followed methodology is a very promising procedure for flood risk mitigation purposes in small basins. The main constraint to the application of this approach is the absolute need of real-time data of the hydrometeorological network. The methodology requires the availability of daily precipitation data as well as hourly precipitation in real time, which is very scarce in Portugal. With the availability of these data, it would be possible to detect when the minimum, maximum, or pre-warning thresholds are exceeded and hence predict possible floods with disastrous consequences for the population. Moreover, this approach must be extended to other regions in Portugal in order to define other regional precipitation thresholds for flood triggering over the country.

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Author Contributions: The methodological approach was designed and written by the two authors; data collection, statistical analysis, and figures were conducted by Mónica Santos. The introduction, the discussion, and conclusions were discussed and written by the two authors.

Conflicts of Interest: The authors declare no conflict of interest.

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